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A STUDY OF THE APPLICATION OF HEAT OR FORCE FIELDS TO THE SONIC-BOOM-MINIMIZATION PROBLEM

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16. Abstract

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SUMMARY

Schemes purporting to offer a solution to the sonic-boom problem by application of a heat or force field to alter the airflow about an airplane in supersonic flight have been advanced and have received a considerable amount of attention, not only in the scientific community but also in the popular press. In this report, the basic concepts of the schemes are related to the known body of information concerning sonic-boom generation, and a variety of problems which would be encountered in attempts at practical application of these schemes are brought out. In addition, a preliminary estimate of the power requirements for a representative supersonic transport is made. The treatment of an illustrative example indicates that, subject to certain simplifying assumptions used in the study, finite rise-time signatures which would practically eliminate the shock-wave noise are theoretically obtainable but require the creation of a carefully controlled heat or force field extending several airplane lengths ahead of and behind the airplane itself. Even for idealized conditions with weightless power generation equipment and with no energy dissipation, it is found that the required power appears to be roughly equivalent to twice that necessary to sustain the airplane in steady level flight.

INTRODUCTION

The sonic boom continues to present one of the most severe problems confronting the advancement of high-speed air transportation. Numerous studies have attacked the problems of defining the dependence of sonic-boom characteristics on airplane configuration variables and of determining configuration requirements for sonic-boom minimization under various constraints. To date none of the studies has offered much hope for attaining sonic-boom disturbances that unquestionably would be acceptable for routine overland operation of supersonic transports.

One of the more intriguing of the configuration-study concepts could theoretically result in a ground overpressure pattern essentially devoid of the shocks which create the sonic boom. As shown in reference 1, if a configuration with the proper shaping could be made long and slender enough, a finite rise-time signature could be made to extend from the airplane to ground level. However, the study also indicates that the required lengths greatly exceed those presently under consideration for future airplane designs.

Other more exotic approaches to solutions of the sonic-boom problems include the application of laser beams or other heat sources as well as the use of electrostatic forces to alter the flow field surrounding the airplane in a way which would favorably modify the pressure pattern and the sonic boom. The most publicized example is the concept requiring the use of electroaerodynamic phenomena presented in reference 2. The considerable amount of attention given to these schemes points out a need for a more fundamental treatment of the concepts than has been given heretofore.

A study of the applicability of these schemes, presented in this report, is based on the belief that they can successfully reduce the sonic-boom annoyance only if employed in such a manner as to produce signatures with reduced shock strength or reduced rate of shock onset in accordance with the well-established laws of sonic-boom generation and propagation. For the purposes of this study, attainment of a finite rise-time signature which could practically eliminate the shock-wave noise is considered to be the objective. The method envisioned to achieve this goal involves the creation of a phantom body enveloping the airplane as a result of the effect of the heat or force field in diverting the airflow. The phantom-body shape would be defined by the altered flow-field streamlines. If the phantom body could be extended well forward and rearward of the actual airplane and could be properly shaped, a finite rise-time ground overpressure signature could be produced.

The present study is concerned with the considerations dictating the required phantom-body shape, the variation in flow properties within the phantom body, and the distribution and magnitude of the power required to divert the flow and create the phantom body. A rather idealized and simplified approach is used. One-dimensional channel flow equations are employed in the solution for the phantom-body characteristics, and no consideration is given to the ultimate source of the heat or force field or the size, weight, and efficiency of the generating equipment. In spite of the idealized nature of the study, it is believed that the results will serve to provide an assessment of minimum power requirements and thus provide a first test of the applicability of the concepts.

SYMBOLS

A_c effective channel area, $A_p - A_e$

A_e airplane effective cross-sectional area due to a combination of volume and lift effects

A_o	initial phantom-body cross-sectional area
A_p	phantom-body cross-sectional area as defined by the streamline boundaries
C_p	pressure coefficient, $\dfrac{p - p_\infty}{\frac{\gamma}{2} p_\infty M^2}$
c_p	specific heat at constant pressure
F	incremental axial force
h	airplane altitude
I_i	the ith influence coefficient
l_p	phantom-body length
M	Mach number
$\dot{m}$	mass flow rate
P	power
p	pressure
Δp	incremental pressure due to flow field of airplane. sonic-boom overpressure
r	radial distance from airplane center line
T_o	stagnation temperature
Δt_r	rise time of sonic-boom pressure signature
V	velocity
x	distance measured along longitudinal axis from initial change in phantom-body area

$\beta = \sqrt{M^2 - 1}$

γ ratio of specific heats

Subscripts:

av average

i,n integers

max maximum

min minimum

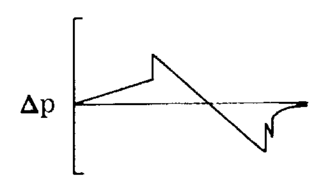
∞ free-stream conditions

THE CONCEPT

In most of the supersonic flight regimes, current airplane designs for supersonic transports are expected to produce an N-wave type of ground pressure signature as illustrated in figure 1(a). Within the configuration design restraints, the application of sonic-boom-minimization concepts permits a shaping of the airplane to effect a moderate reduction of the magnitude of the disturbances; however, the abrupt pressure rise remains and the boom is reduced but not eliminated. Studies, such as those reported in reference 1, in which realistic design restraints have purposely been ignored show that a sufficiently long and slender airplane with proper shaping would produce a pressure signature having a finite rise time and virtually no sonic boom. The required airplane lengths, however, exceed present-day expectation by such a large amount that this approach seems hopeless.

Recent suggestions for sonic-boom alleviation by more exotic schemes such as the use of laser beams or electrostatic forces, as proposed in reference 2, have led to speculation regarding their use to create the effect of a long slender airplane. That, in fact, is the only way envisioned by the authors for these schemes to bring about the desired improvements. In application, a heat field or force field would be created in the region surrounding the airplane. The field would extend well forward and rearward of the airplane itself and would have to be distributed carefully to create streamlines similar to those depicted in figure 1(b). Although it may not be apparent in the figure, the streamlines, which define the shape of the phantom body, extend to infinity in both the forward and rearward directions. The flow field external to the phantom body, and thus the sonic boom, would depend on the phantom-body shape and not on the airplane itself. With a sufficiently long phantom body as shown here, a sonic-boom signature having a finite rise time could be created.

In figure 2 is shown a representative plot of the area development of a phantom body designed to envelop the airplane and bring about the desired sonic-boom benefits. Also shown in figure 2 are plots of the resulting pressure coefficient on the phantom-body surface and the ground overpressure produced by the phantom body. The difference between the phantom-body cross-sectional area and the effective cross-sectional area of the airplane must be generated by the action of the heat or force field on the stream tube of air entering the phantom body. In order that no expansions or compressions occur outside the region under consideration, the stream-tube inlet and exit conditions must correspond to those of free-stream air. In the interest of simplicity and to reduce the complexity of the calculating procedure, flow variations within a single channel are assumed to be sufficient to provide the distribution of local compressions and expansions necessary to produce the desired streamlines at the phantom-body surface. It is recognized that the application of this concept to a specific airplane configuration would require a detailed three-dimensional description of the heat or force field within the single channel and would thereby necessitate the consideration of not one but a multitude of stream tubes. Within each stream tube, heat- or force-field-created expansions would interact with airplane-created compressions very near the airplane surface to prevent the formation of shocks. It is also recognized that for strong shocks formed immediately at the airplane surfaces, the stream-tube expansions might not be fully effective in providing a cancellation. In this particular instance, a pressure signature on the ground could appear as shown in the sketch rather than as the smooth shape shown in figure 2; however, a typically pointed airplane nose or a subsonic-leading-edge wing need not form strong shocks immediately at the surface and cancellation should be possible. Also, in regard to the practical application of this concept, consideration must be given to the effect of the phantom-body flow in altering the aerodynamic and flow-field characteristics of the airplane itself.



The crude treatment afforded by the single average stream tube rather than the multitude discussed in the preceding paragraph is believed to be sufficient to provide a qualitative assessment of the problems involved and a first-order estimate of the power requirements of such systems. The behavior of the air within the phantom body is studied by means of one-dimensional channel flow equations, and the corresponding cross-sectional areas are termed channel areas.

THEORETICAL ANALYSIS

The numerical method for calculating the theoretical power requirements necessary to influence the airflow properly is based on the assumption that the stream tube of air which is to be shaped around the airplane can be treated as steady, one-dimensional, inviscid channel flow of a perfect gas with no heat transfer across the streamline boundaries.

For a given airplane configuration, given flight conditions, and a desired sonic-boom signature, the phantom-body area development can be determined by using methods described by Barger (ref. 3) and the surface pressures can be calculated by using small-disturbance theory applied to open-nosed bodies of revolution (refs. 4 and 5). Having established the area development and pressure distribution, which actually are the boundary conditions of the problem, the governing differential equations can be written in terms of influence coefficients (ref. 6).

For the heat-addition case, the differential equations which apply to an element of fluid are

$$\frac{dT_o}{T_o} = I_1 \frac{dp}{p} + I_2 \frac{dA_c}{A_c} \tag{1}$$

$$\frac{dM^2}{M^2} = I_3 \frac{dA_c}{A_c} - I_4 \frac{dT_o}{T_o} \tag{2}$$

and for the force-field case, the differential equations are

$$\frac{dF}{pA_c} = I_5 \frac{dp}{p} + I_6 \frac{dA_c}{A_c} \tag{3}$$

$$\frac{dM^2}{M^2} = I_3\left(\frac{dA_c}{A_c} - \frac{dF}{pA_c}\right) \tag{4}$$

where the influence coefficients are defined as

$$\left.\begin{aligned}
I_1 &= \frac{\beta^2}{\gamma M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)} & I_4 &= \frac{1}{\beta^2}\left(1 + \frac{\gamma - 1}{2} M^2\right)\left(1 + \gamma M^2\right) \\
I_2 &= \frac{1}{1 + \frac{\gamma - 1}{2} M^2} & I_5 &= \frac{\beta^2}{1 + (\gamma - 1)M^2} \\
I_3 &= \frac{2}{\beta^2}\left(1 + \frac{\gamma - 1}{2} M^2\right) & I_6 &= \frac{\gamma M^2}{1 + (\gamma - 1)M^2}
\end{aligned}\right\} \tag{5}$$

For both the heat-addition and force-field cases, the numerical techniques for handling the problem are the same. First, the stream tube is divided into increments along the axis; and, in general, each element of the stream tube is designated by forward and rearward stations of i and $i + 1$, respectively. By assuming that all parameters vary linearly along the element, the differential parameters of the governing equations can be expressed as illustrated in the following example of area variation:

$$\frac{dA_c}{A_c} = 2\left(\frac{A_{i+1} - A_i}{A_{i+1} + A_i}\right)$$

Solutions for the sets of equations (1) and (2) or (3) and (4) are found by applying an iteration routine which cycles through one stream-tube increment at a time and obtains a solution before considering the next increment. The first cycle uses the Mach number at station i to evaluate the influence coefficients and to obtain a value of dM^2/M^2 across the increment. The first trial value of M_{i+1} is given by

$$M_{i+1} = \left[\left(\frac{dM^2}{M^2}\right)M_i^2 + M_i^2\right]^{1/2}$$

and an average Mach number M_{av} for the increment is given by

$$M_{av} = \frac{1}{2}\left(M_i + M_{i+1}\right)$$

Influence coefficients based on M_{av} are then computed, a new value of dM^2/M^2 results, and a second trial value of M_{i+1} is obtained from

$$M_{i+1} = \left[\left(\frac{dM^2}{M^2}\right)M_{av}^2 + M_i^2\right]^{1/2}$$

This procedure is continued until a sufficiently converged value of M_{i+1} is obtained for the increment being considered and the entire iterative procedure is repeated to obtain solutions for all successive increments. It is then possible to determine the power required by the system to retard or accelerate the flow properly and to maintain the desired diversion of the streamline boundaries. For the heat-addition case each increment of stream-tube volume must receive energy at the rate of $c_p\left(T_{o,i+1} - T_{o,i}\right)\dot{m}$. The total power for the system through the nth station is given by

$$P = \dot{m}\sum_{i=1}^{n} c_p\left(T_{o,i+1} - T_{o,i}\right)$$

Considering the force-field case, the power requirement for one increment of the stream tube is $F_i V_\infty$ where

$$F_i = \left(\frac{F}{pA_c}\right)_i \left(\frac{A_{c,i+1} + A_{c,i}}{2}\right)\left(\frac{p_{i+1} + p_i}{2}\right)$$

The total power for the system through the nth station is

$$P = V_\infty \sum_{i=1}^{n} F_i$$

Under these assumptions, it is possible to estimate the power requirements necessary to influence the flow field around an airplane in such a way as to improve substantially its sonic-boom characteristics.

RESULTS AND DISCUSSION

The problems encountered in employing the phantom-body concept to minimize the sonic boom can best be explained by applying this concept to an actual airplane configuration. A typical proposed supersonic transport configuration having a length of 93.27 meters (306 ft) and a cruise Mach number of 2.7 at an altitude of 18.6 kilometers (61 000 ft) is the basis of the following discussion. The cruise weight of the airplane is assumed to be 260 820 kg (575 000 lbm), and no account is taken of weight increases due to onboard equipment required to generate the phantom body.

The variation of several important flow properties within the phantom body and the local and total power requirements of the system are shown in figure 3. For both the heat- and force-field cases, similar changes in aerodynamic performance due to Mach number effects would be expected since both cases seem to exhibit approximately the same Mach number variations. The stagnation temperature reaches a maximum of approximately 135 percent of the free-stream value for heat addition and remains constant for the force-field application. The other plots indicate the local and total power requirements for the system. The local power is indicative of the required heat or force distribution along the phantom-body axis. For both cases the local power distributions behave somewhat erratically because a real airplane area development, which naturally possesses some irregularities, was used in this example to identify actual problem areas. This plot indicates that a problem may arise in the establishment of a force-field or heat source and sink distribution which possesses such large longitudinal gradients. Also the positive and negative local power values indicate that it will be necessary to remove as well as to add power to the flow. The most pronounced problem appears to be the maximum total power requirement. Even though the force-field case requires 35 percent less total power than the heat addition, an exceptionally large amount of power (approximately 550 megawatts (738 000 hp)) must be provided for the portion of the system ahead of the airplane nose; this amount is approximately twice the power required to maintain steady level flight at the assumed flight conditions.

An important factor in analyzing the phantom-body concept is the selection of the phantom-body capture area A_o. Varaiations in the flow properties and the maximum power requirements with changes of A_o are shown in figure 4. As expected, the flow properties are very sensitive to A_o for small values of A_o; therefore, to avoid large changes in the flow properties which in turn alter the airplane performance characteristics, a large A_o is desired. The maximum power, however, is fairly insensitive to changes in A_o throughout the range considered; thus, an A_o of 46.5 meters^2 (500 ft^2) appears to be a reasonable selection for both the heat-field and force-field cases.

The phantom-body length is also a significant factor upon which the sonic-boom signature characteristics as well as the power requirements depend. Figure 5 shows how the maximum ground overpressure Δp_{max} decreases and the rise time Δt_r increases as the phantom-body area development of figure 2 is stretched out. In selecting a reasonable body length, no values less than 320 meters (1040 ft) are considered because lengths less than 320 meters produce no finite rise time. No allowance has been made for the somewhat reduced lengths which may result from a more exacting treatment of real atmosphere effects as pointed out by Seebass in reference 7. As expected, the power requirements for both the heat- and the force-field application increase with increasing length. In this situation, the desired rise time is the primary factor for defining the necessary phantom-body length and the maximum power requirements.

To complete this study of the phantom-body concept, a brief presentation of the changes in sonic-boom characteristics and power requirements which are expected to accompany changes in Mach number and altitude is included. This study is intended to indicate trends only; thus, the set of curves in figure 6 was generated by considering other Mach numbers and altitudes as variations from the $M = 2.7$, $h = 18.6$ kilometers example.

The airplane effective-area development was corrected for changes in Mach number and altitude. To account for the major factors in the simplest manner possible, the airplane area development was assumed to remain unaltered by changes in Mach number; however, the equivalent area due to lift was assumed to vary in magnitude but not in distribution with changes in Mach number and altitude.

For each variation in Mach number and altitude, the appropriate phantom-body area development was initiated at a distance sufficiently ahead of the airplane nose to produce a rise time of 0.1 second. The relationship between the relative loudness and the rise time (ref. 8) indicates that some benefit can be realized from rise times of 15 to 20 milliseconds; however, since no appreciable decrease in power is attained by employing these smaller rise times (fig. 5), a rise time of 0.1 second was selected for this portion of the study in an attempt to provide a margin against the adverse effects of atmospheric distortion. Based on the results shown in figure 4, a phantom-body capture area of 46.5 meters^2 (500 ft^2) was incorporated into the area development for all conditions.

The results of the study shown in figure 6 indicate that power requirements become less for lower Mach numbers, but not to such an extent that the scheme appears to be more practical. For higher Mach numbers, which are more attractive from an economic standpoint, the power requirements are greater. For a given Mach number, power requirements are not significantly less at altitudes above or below those normally selected for cruise economy.

CONCLUDING REMARKS

A study has been made of the potential benefits to be gained, the problems encountered, and the power required in the application of heat- or force-field concepts to the sonic-boom-alleviation problem. The treatment of an illustrative example for a proposed supersonic transport configuration at a cruise Mach number of 2.7 indicates that, subject to the simplifying assumptions made in the study, finite rise-time signatures which would practically eliminate the shock-wave noise are theoretically obtainable but require the creation of a carefully controlled heat or force field extending several airplane lengths ahead of and behind the airplane itself. A complicating factor is the not insignificant variation of the flow properties within the phantom body which alters the airplane aerodynamic performance. There is also some doubt that, in the practical application of these schemes, airplane-produced shocks could be completely cancelled and thereby prevented from penetrating the phantom body and propagating to the ground. Under the simplifying assumptions of this study and for idealized conditions with weightless power generation equipment and no energy dissipation, a power expenditure roughly equivalent to twice that necessary to sustain the airplane in steady level flight would be necessary to create the heat field or force field ahead of the airplane. It was also discovered that not only must some means be found to deliver continuously large quantities of power to the air in the proper manner, but means must also be provided to extract power from the air in a prescribed manner. Thus, although the net power requirement is zero for this simplified and idealized analysis, the significant fact is that tremendous amounts of energy must be generated and then, by some process yet unknown, returned to the airplane. The employment of a highly sophisticated power circulation device of tremendous capacity thus appears to be a requirement. It must also be recognized that consideration of the additional equipment weight and consideration of the system energy losses would further increase the power generation requirements. Further study indicates that the power requirements for comparable finite rise-time signatures are not significantly less at altitudes above or below those normally selected for cruise at a given supersonic Mach number.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 28, 1969.

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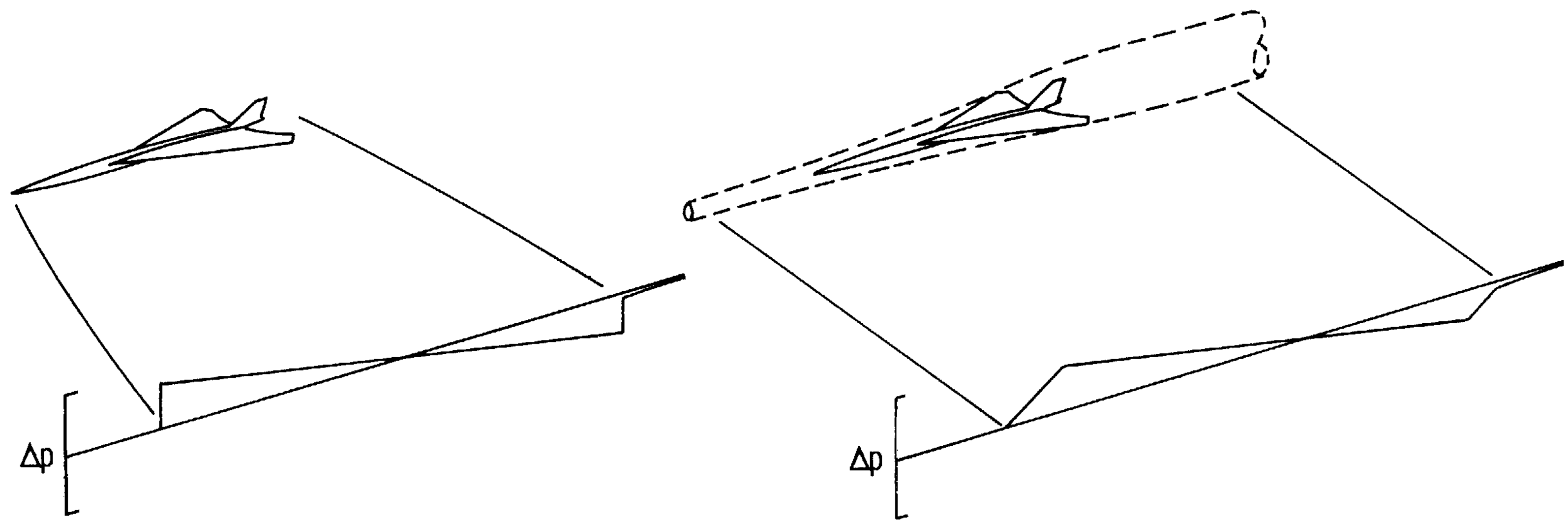

(a) Airplane alone.

(b) Airplane with enveloping phantom body.

Figure 1.- Pictorial representation of phantom-body concept of sonic-boom minimization.

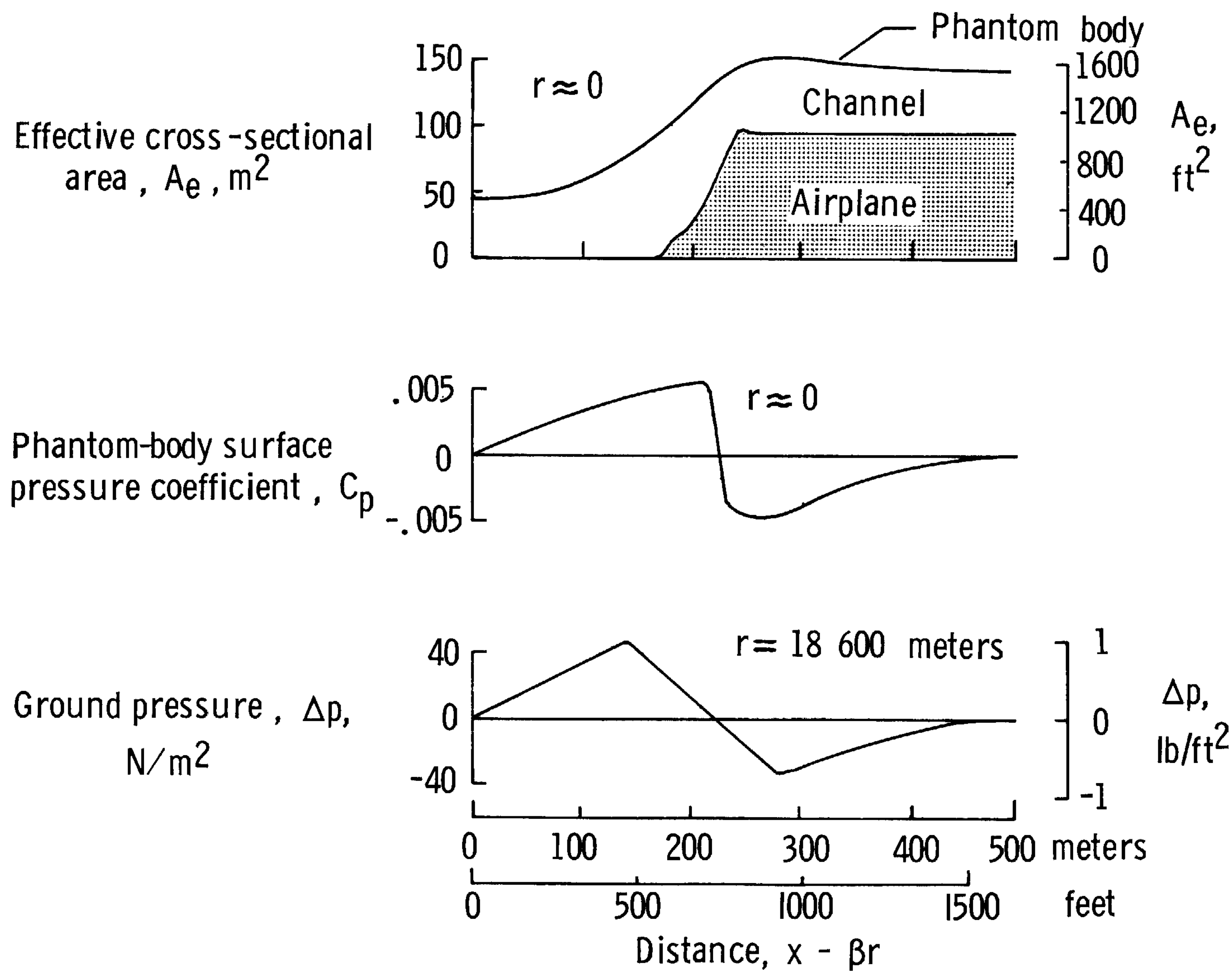

Figure 2.- Pressure pattern resulting from application of phantom-body concept to supersonic transport. $M = 2.7$; $h = 18.6$ kilometers (61 000 ft).

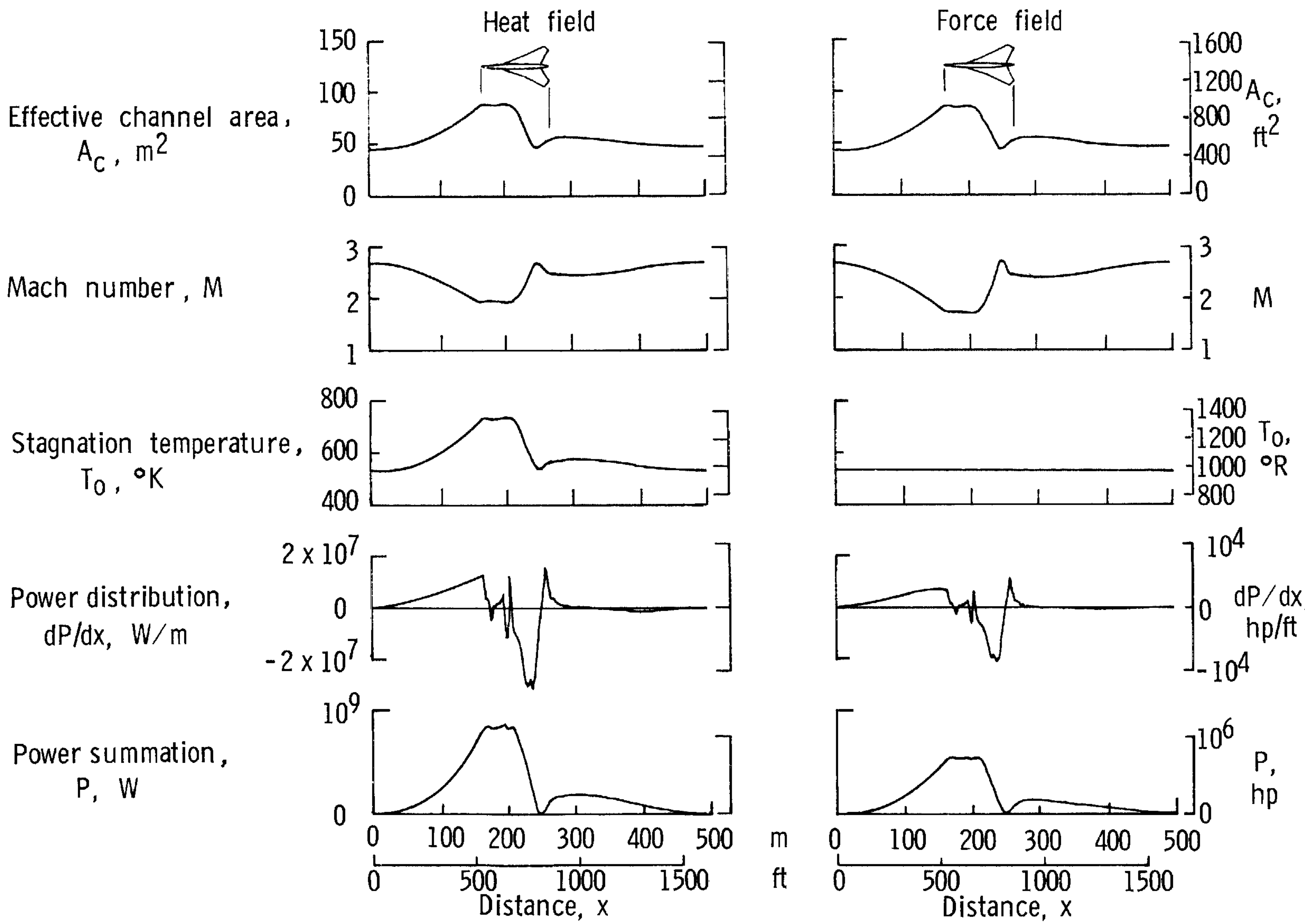

Figure 3.- Variation of phantom-body flow properties and power requirements along longitudinal axis for example of figure 2.

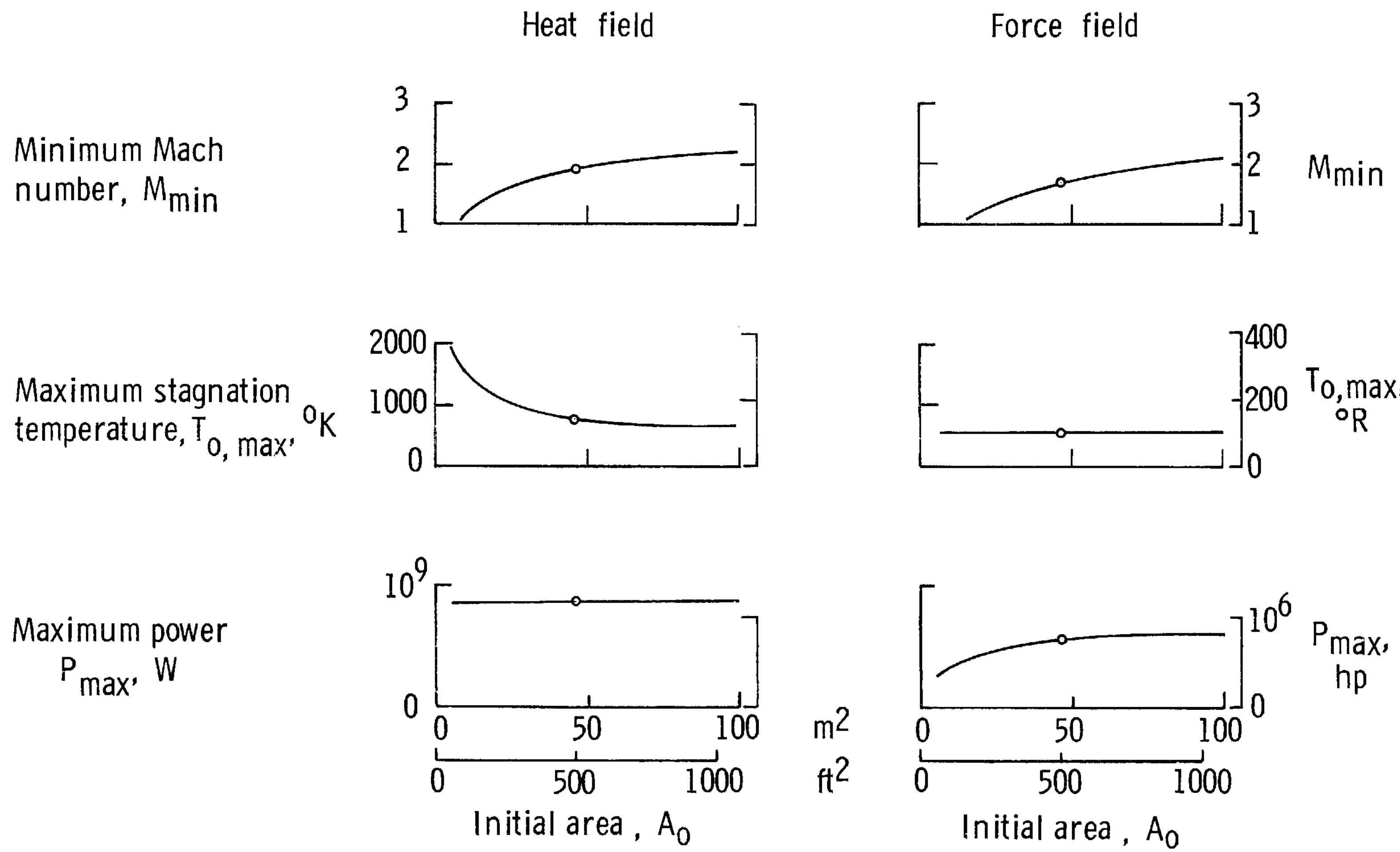

Figure 4.- Variations of phantom-body flow properties and power requirements with changes of initial phantom-body area. Circular symbols denote initial phantom-body area assumed in example of figure 2.

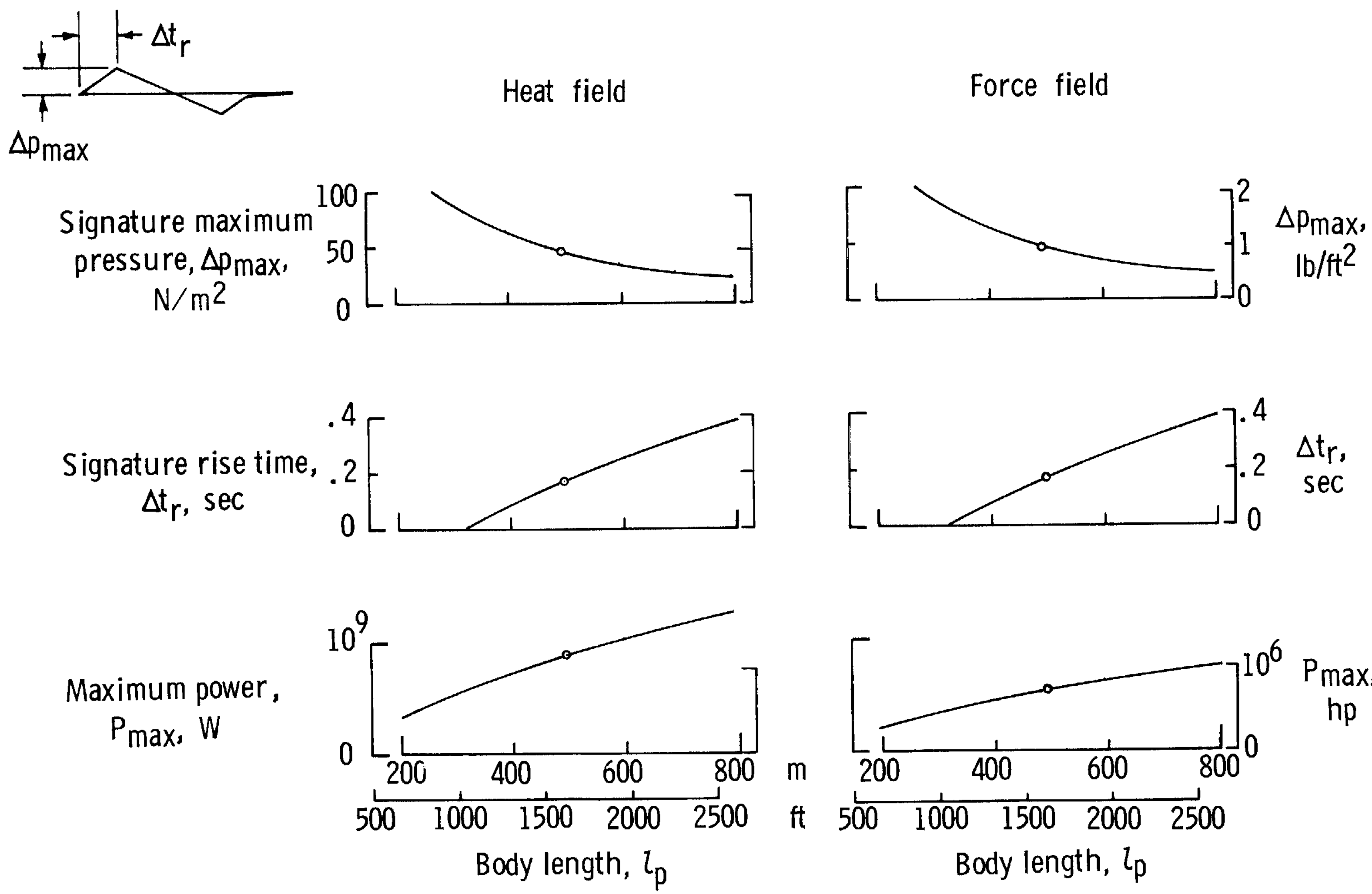

Figure 5.- Variations of signature characteristics and corresponding power requirements with changes of phantom-body length. Circular symbols denote phantom-body length assumed in example of figure 2.

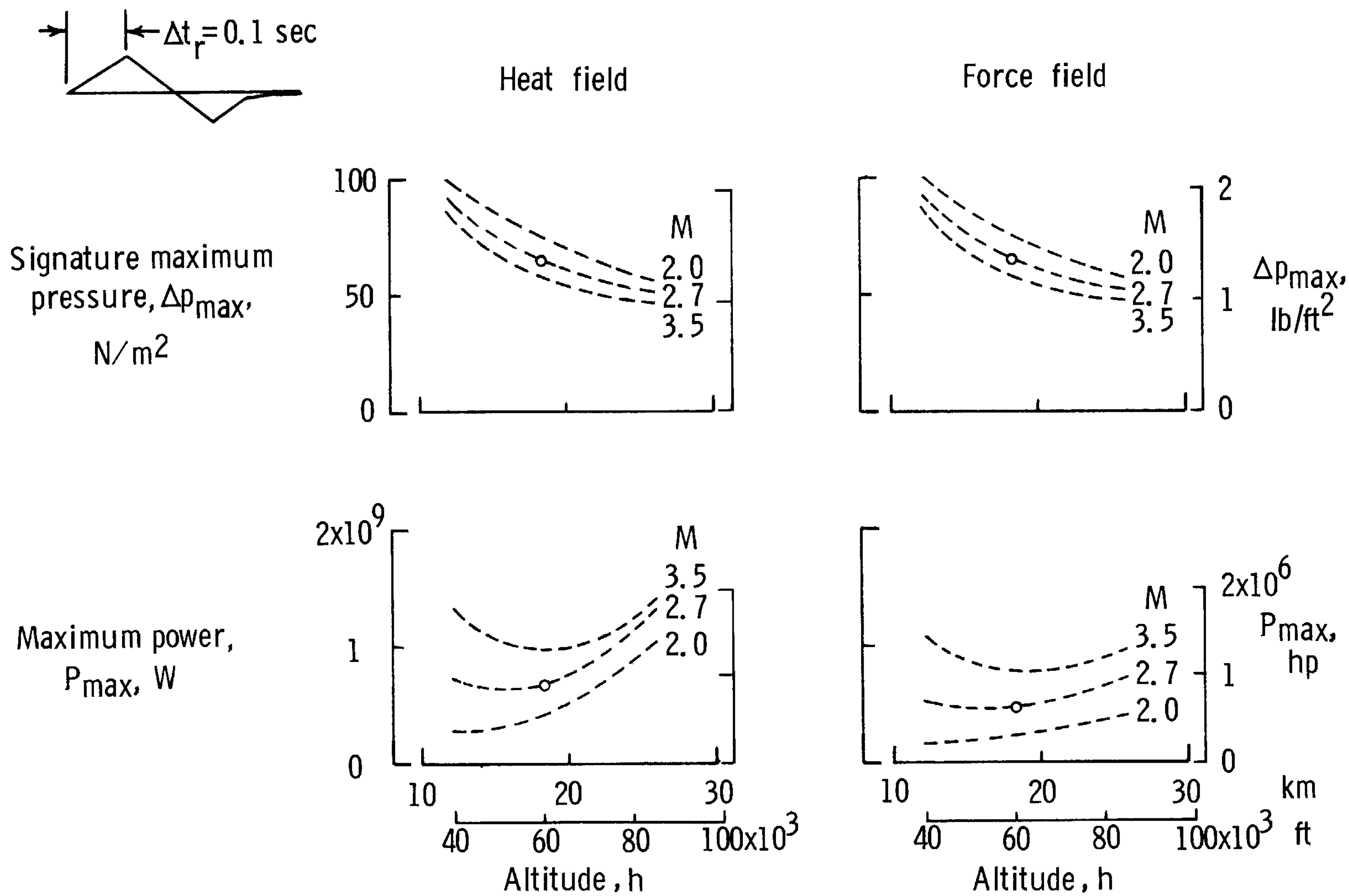

Figure 6.- Variations of signature characteristics and corresponding power requirements resulting from application of phantom-body concept to supersonic transport for various cruise altitude and speed conditions. Phantom-body lengths selected to give rise time of 0.1 sec; circular symbols denote conditions at M = 2.7 and h = 18.6 kilometers (61 000 ft).

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